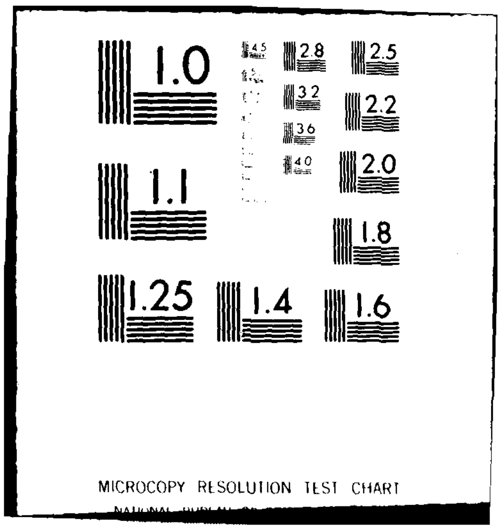
AD-A090 454 ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND DOVER--ETC F/G 19/5
ION IMPLANTED GUIDED WAVE DEVICES FOR ARMY FIRE CONTROL,(U)
JUN 80 J M ZAVADA, H A JENKINSON, T J GAVANIS

UNCLASSIFIED NL

1 OF 1
AD A
090454

END
DATE
FILMED
11-80
DTIC


1.0
4.5
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART

ION IMPLANTED GUIDED WAVE DEVICES FOR ARMY FIRE CONTROL

JOHN M. ZAVADA, [redacted]
HOWARD A. JENKINSON, [redacted]
THOMAS J. GAVANIS, [redacted]
~~Fire Control and Small~~ Caliber
Weapon Systems Laboratory
ARRADCOM, Dover, NJ 07801

ROBERT G. HUNSPERGER, DR.
University of Delaware
Newark, DE 19711

DONALD C. LARSON, DR.
Drexel University
Philadelphia, PA 19104

JAMES COMAS, DR.
Naval Research Laboratory
Washington, DC 20375

I. INTRODUCTION

In a recent review of the Army's Fire Control Technology Base(1), several key issues were repeatedly emphasized. One of these issues was that future fire control systems will have to meet certain stringent requirements in order to permit the Army to successfully engage hostile forces in anticipated combat scenarios. Prominent among these requirements are minimum acquisition/reaction time, multiple target engagement capability, increased first round hit probability, and 24 hour/all weather operation. The first three requirements clearly indicated the need for sensing and signal processing subsystems capable of handling large amounts of digital and analog information and of processing this information rapidly. In spite of the major advances that have been made in the field of microelectronics, this need is still a

formidable challenge to Very Large Scale Integration (VLSI) circuits and to Very High Speed Integrated Circuits (VHSIC). Another possible solution to this problem lies in the development of fire control systems incorporating guided wave components. Guided wave or optical devices are the analogs of the familiar electronic devices such as cables, modulators, switches, sources and detectors, which rely on the motion of electrons and their subbsequent deflection. However, optical devices guide an electromagnetic (EM) wave through a material structure and function directly on the propagating wave. Due to the higher carrier frequencies of optical waves, the information that guided wave devices can process is nearly 10,000 times greater than that of electronic devices. Also, these optical devices are several orders of magnitude faster than their electronic counterparts. Other advantages of guided wave devices include: lower transmission losses, virtually complete immunity to EM interference and countermeasures, and the elimination of use of strategic materials such as copper. Once these devices are integrated into optical circuits, there are additional benefits of greater reliability and durability.

The development of integrated optical circuits parallels very closely the development of integrated electronic circuits. First there was the use of discrete electronic elements such as transistors, capacitors, and oscillators. This corresponds to the use of discrete optical elements such as lenses, prisms, and lasers in current optical systems. Later the discrete electronic devices were assembled into circuit boards and, eventually, into monolithic integrated circuits. Similarly, the goal of "Integrated Optics" is to minimaturize and assemble the discrete optical elements and devices into a monolithic circuit a few square millimeters in area. This size reduction of optical systems is even more dramatic than what has been accomplished in the electronics area.

While there has been considerable activity in both the military and civilian sectors to utilize guided wave devices in communication systems, such as telephone and television, the potential of this technology for sensing and optical signal processing roles has been largely untapped. The few military programs that are developing guided wave components for these applications include the work on a radio frequency (RF) spectrum analyzer(2), on optical correlators(3), and on fiber optic sensors(4).

Due to the fourth requirement mentioned above for 24 hour/all weather operation, the Army has been emphasizing systems which operate at longer wavelengths, in particular, at infrared and millimeter

474

A

wave (MMW) frequences. Active devices, such as carbon dioxide (CO_2) lasers and MMW transmitters, form a natural basis for additional applications of guided wave technology to Army Fire Control Systems. Typical systems which could utilize infrared optical circuits include CO_2 laser radars, Miss Distance Sensors (MDS) and sensors for smart munitions such as Smart Target Acquisition Fire and Forget (STAFF). These optical circuits could be used to perform various functions including phased array transmission, heteroyne detection, parallel processing and optical correlation.

Various methods have been used to fabricate optical waveguides and components. These include thin film deposition, epitaxial growth, filled channel techniques, ion diffusion and ion implantation. The latter method is a particularly interesting technique that offers a number of distinct advantages in comparison to the other methods. In ion implantation a beam of atoms is ionized, accelerated through a potential difference, and is directed at a suitable material target. The resulting damage in the material and the introduction of foreign atoms can produce electronic, chemical, and optical changes. In fact, ion implantation is one of the major production techniques used in the electronics industry for the manufacture of integrated electronic circuits. The primary advantage of this technique lies in the precise, external manner by which doping of materials can be controlled. Any ion species can be introduced into a given material and the dopant concentration is not limited by ordinary solubility considerations. The dosage can be monitored very accurately and the depth profile of the implanted ions can be controlled by adjusting the energy of the accelerator. This permits realization of dopant profiles that could not be achieved by diffusion or any other technique. Also, implantation of materials can be performed over a wide range of temperatures allowing for unique interactions of the implanted ions. This technique is a relatively simple procedure which is compatible with modern masking methods used to achieve special configurations of the doped regions. Additionally, there is the possibility that entire optical circuits can be "written" directly on a chip without the use of masks.

While ion implantation has been used to fabricate guided wave components at visible and near infrared wavelengths, little effort has been directed towards applying this technique to form guided wave devices in the far infrared. Lincoln Laboratories has made low loss waveguides at 10.6 microns through proton implantation of cadmium telluride(5). However, a drawback to this work is the very

475

high accelerating energies, over 1 MeV, that were required. Accelerating machines, capable of such large energy outputs, are not readily available and are very costly to operate. If it were possible to fabricate low loss infrared waveguides with moderate energy accelerators (less than 300 keV), then ion implantation would be established as a prime fabrication technique for integrated optics in this spectral region.

This is the task that we are addressing in our current research effort: to determine the feasibility of fabricating infrared waveguides in semiconductor materials using moderate energy ion implantation. Semiconductor materials were selected for this work because all of the major functions of an optical circuit, such as light generation, waveguiding, modulation and detection, can be achieved in these materials.

II. OPTICAL WAVEGUIDES

The basic component in an integrated optical circuit is the waveguide. This structure serves to confine the EM wave to a particular region and to specify the direction of propagation of this wave. Figure 1 illustrates the operation of a planar (two dimensional) waveguide. In this figure, we assume that the EM wave has already been introduced into the waveguiding region. This can be accomplished through various methods including endfire coupling, or even light generation in the waveguide. The waveguide in this figure is formed by the middle region identified by its optical index of refraction, n_f. The regions above and below the waveguide are similarly labelled by their indices n_o and n_s. For the EM wave to be guided in the middle region, it is necessary that n_f be larger than either n_o or n_s. When this condition is satisfied, there exists an angle of incidence at each interface, called the critical angle, above which the incident wave will be totally reflected. The guided wave will then propagate in a zig-zag fashion undergoing total internal reflection at each interface. Upon each reflection the EM wave will experience a change in phase. For the wave to be propagated, these phase changes, in addition to the phase change resulting from the optical path difference, must add constructively. This leads to an eigenvalue equation, one for each polarization, which determines the propagating modes in the waveguide. For lossless media, the basic eigenvalue equation is (6) :

$$k n_f t \cos\theta_f - \Phi_{fo} - \Phi_{fs} = \nu\pi \qquad k = \frac{2\pi}{\lambda_o} \qquad \nu = 0, 1, 2, 3\ldots \tag{1}$$

476

where t is the thickness of the waveguiding region, θ_f the angle of propagation of the guided wave in the film, λ_o the wavelength of the EM wave in free space, Φ_{fo} and Φ_{fs} the phase change due to reflection at the respective f-o and f-s interface, and j is the modal order. The phase changes can be calculated from the Fresnel reflection coefficients for a planar interface and are given by:

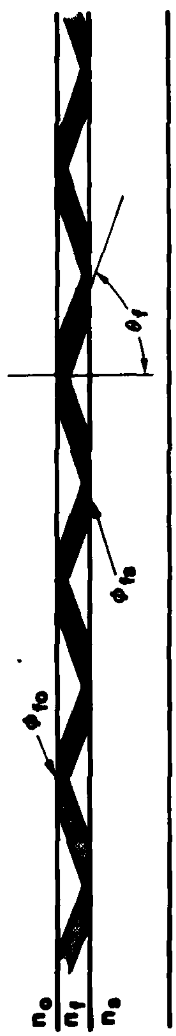
$$\tan \Phi_{fi} = \frac{(n_f^2 \sin^2 \theta_f - n_i^2)^{\frac{1}{2}}}{n_f \cos \theta_f} \tag{2}$$

for s polarization, and by:

$$\tan \Phi_{fi} = \left(\frac{n_f}{n_i}\right)^2 \frac{(n_f^2 \sin^2 \theta_f - n_i^2)^{\frac{1}{2}}}{n_f \cos \theta_f} \tag{3}$$

for p polarization. Here the subscript i refers to either the region above the waveguiding layer (i = o) or to the region below (i = s) depending upon the phase change under consideration. The guided modes in a planar waveguide are usually denoted TE_j and TM_j, where TE is transverse electric (parallel polarization) and TM is transverse magnetic (perpendicular polarization). Once the optical indices are known, the eigenvalue equations can be solved to determine the number of guided modes for a given value of the waveguide thickness. The resulting set of curves for a particular choice of optical indices is shown in Figure 2. As can be seen in this figure, curves corresponding to different modal orders are widely separated as compared to curves of the same modal order but different polarization. This means that the propagating modes of the same order normally occur in doublets, one for each polarization, and are distinct from the doublet for the next order.

The above equations can also be used to determine the optical index and the thickness of the planar waveguide provided that the waveguide can support at least two propagating modes and that the optical indices n_o and n_s are known. Then, by measuring θ_f for each mode, and by substituting this angle into Eq. (1) with the appropriate expressions for the phase changes, a set of simultaneous, transcendental equations involving two unknowns can be obtained. These equations can be solved numerically to yield the parameters n_f and t of the waveguiding layer.



$n_f > n_s > n_o$

Figure 1. Planar Optical Waveguide

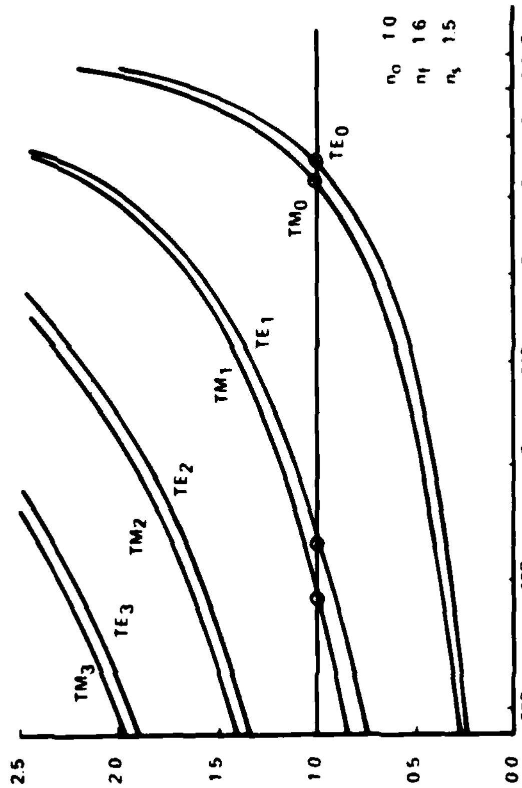


Figure 2. Predicted Waveguide Modes

478

During the current fiscal year, this method was used to determine the thickness and the refractive index of thin film aluminum oxide waveguides. These planar waveguides were prepared by evaporation of aluminum oxide onto glass substrates in Fire Control Division's thin film laboratory. In order to couple laser light into the waveguide and to measure the angles of propagation for the guided waves, an optical facility, sketched in Figure 3, was assembled. This facility consists of a helium neon (HeNe) laser source (0.6328 microns), a beam collimator, and a stage which holds both the planar waveguide and a high index glass prism (optical index 1.732). The prism is used to couple the laser light into the waveguide and the stage is mounted on a motorized rotary table. Figure 4 contains a schematic drawing of the prism coupling technique in which the collimated HeNe laser beam impinges on the glass prism at an incident angle θ, is refracted to the corner of the prism where, at certain distinct angles, it is coupled into the waveguide. The rotary table allows the incident angle to be varied until waveguiding is achieved, as indicated visually by the slide flashing with the red HeNe light. While the film was highly transparent at this wavelength it did contain inhomogeneities and surface roughness which resulted in light being scattered out of the waveguide. This scattering is responsible for the flame-like pattern in the slide during coupling. For a perfect film, the waveguided light would be visible only at the end of the film where light would be scattered back into the air. Measurements were made of the coupling angle for each polarization of the propagating modes. Once the coupling angle has been measured, the angle of propagation in the waveguide is determined by (7):

$$\sin\Theta_f = \frac{n_p}{n_f}\sin\left\{\sin^{-1}\left(\frac{n_o}{n_p}\sin\Theta\right)+\Theta_c\right\} \quad (4)$$

where θ_c is the corner angle of the prism and n_p is the prism's optical index. In order to couple light by this technique into every mode of the waveguide, it is necessary that $n_p > n_f$.

Results of this experiment for one of the thin film waveguides are contained in Table I. There, the incident coupling angle, the excited mode and the angle of propagation are listed. Below the table are stated the calculated values for the thickness and the

479

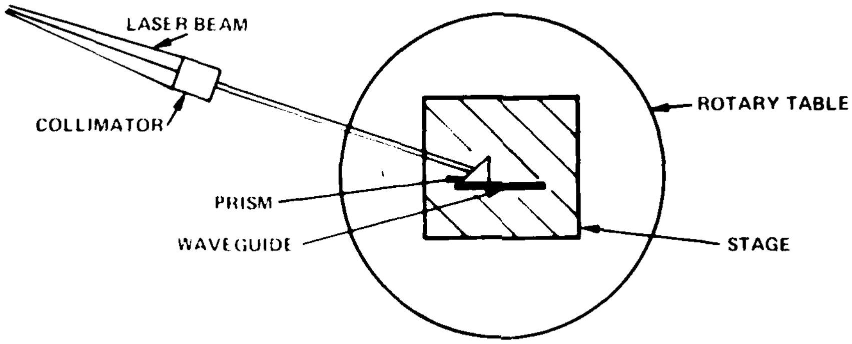


Figure 3. Experimental Facility

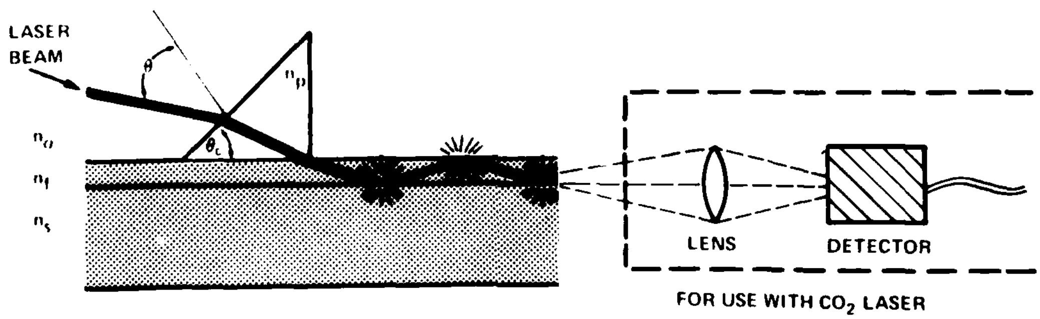


Figure 4. Prism Coupling Technique

(480)

TABLE I. Prism Coupling Parameters

θ	MODE	θ_f
48.75°	TE_0	82.27
48.50°	TM_0	82.01
39.75°	TE_1	74.50°
38.75°	TM_1	73.86°
29.75°	TE_2	67.46°

LASER WAVELENGTH	0.6328	MICRONS	
PRISM INDEX	1.732		
WAVEGUIDE INDEX	1.650	±.001	
WAVEGUIDE THICKNESS	1.18	±.015	MICRONS

optical index based on this data. The experimental accuracy in measuring the coupling angle is estimated to be $\pm$ 0.1° in this method. This results in an error of $\pm$ 0.015 microns for the thickness and of $\pm$ 0.001 for the optical index.

Channeled, or three dimensional, waveguides are the structures that will be eventually required in integrated optical circuits. In such circuits, the guided wave will have to be switched, coupled into other waveguides, polarized, filtered, modulated, and converted into electrical signals. This processing and conversion is more efficient in channeled waveguides. While the description of modes in a channeled waveguide is more complicated, the same concepts, discussed above, of total internal reflection and constructive interference apply. The guided modes in this case are specified TE_{jk} and TM_{jk} with two modal numbers j and k now being necessary. These modes are likewise determined by eigenvalue equations similar in form to Eq. (1).

III. ION IMPLANTED WAVEGUIDES

In crystalline semiconductor materials, ion implantation can produce a change in the refractive index through various physical mechanisms. These mechanisms include: damage to the crystal lattice resulting ultimately in an amorphous region; introduction of dopant atoms into the lattice causing a change in the polarizability of the unit cell; localized regions of stress in the lattice due to damage and the presence of large numbers of dopant atoms in these regions; and, the compensation of the free carrier of dopant atoms into the lattice causing a change in the polarizability of the unit cell; localized regions of stress in the lattice due to damage and the presence of large numbers of dopant atoms in these regions; and, the compensation of the free carrier concentration in suitably doped materials. This last mechanism has been the primary method used to form optical waveguides in semiconductor materials through ion implantation(8). Naturally, in any actual implantation the above mechanisms are interrelated and the change in the refractive index of the implanted material is due to the total effect of these processes. However, it is possible, by careful design of the experimental conditions, to accentuate one of these mechanisms and to minimize the effects of the others. The present research experiments are centered on free carrier compensation since this mechanism appears to afford the greatest flexibility in altering the optical properties of the implanted regions.

482

For a homogeneous, isotropic, n-type crystalline semiconductor, the relative dielectric constant K can be expressed as the sum of two contributions:

$$K = K_L + K_{FC} \tag{5}$$

where K_L is the relative dielectric constant due to the atoms in the lattice and K_{FC} is the contribution from the free carriers. Usually, K is a complex quantity with the imaginary part being related to the absorption in the material. The refractive index is also a complex quantity and is given by:

$$n = \sqrt{K} = n_1 - in_2 \tag{6}$$

Where n_1, is related to the phase of the EM wave in the material and n_2 is the extinction coefficient.

In the classical treatment of the free carriers as a plasma gas, the contribution to the dielectric constant is:

$$K_{FC} = \frac{-\omega_p^2}{\omega(\omega - ig)} \; ; \; \omega_p^2 = \frac{e^2 N_c}{\epsilon_0 m^*} \; ; \; g = \frac{e}{\mu m^*} \tag{7}$$

Here ω_p is the plasma frequency, ω the angular frequency of the EM wave, g the damping coefficient, e the charge of the electron, N_c the density of free carriers, ϵ_0 the vacuum permittivity, m* the effective mass of the carriers and μ the mobility of the carriers.

During ion implantion of a doped semiconductor, the energetic ions produce displacements in the lattice which, in turn, trap some of the free carriers. This reduction of the carrier concentration results in an increase to the refractive index of a surface layer whose thickness is approximately equal to the penetration range of the implanted ions. Assuming complete compensation of the free carriers in this layer, the change in the dielectric constant is simply K_{FC}. For frequencies below that of the bandgap and for materials in which g is small, the change in the refractive index can be approximated by:

$$\Delta n \sim \frac{1}{2n_1}\left(\frac{\omega_p}{\omega}\right)^2 \tag{8}$$

483

provided that the damage produced in the lattice by implantation is minor. The optical index of the implanted region will be $n_1 + \Delta n$ which is larger than that of the unimplanted substrate, n_1. Then, if the thickness of this region is large enough for Eq. (1) to be satisfied with these values for the optical indices, the implanted layer will form an optical waveguide. As an example, for n-type GaAs with a carrier concentration of $1.1 \times 10^{18}/cm^3$, $\Delta n = 0.225$ at a wavelength of 10.6 microns and the implanted region must have a thickness of at least 2.25 microns in order that optical waveguiding can occur.

A difficulty with this carrier compensation technique is that the remaining free carriers in the substrate can lead to absorption losses. The formal solutions to Maxwell's equations for optical waveguiding show that even though there is total internal reflection at each interface a portion of the EM field extends into the surrounding regions. If the thickness of the waveguide is just above the minimum thickness, then the field in the substrate will be appreciable. Consequently, for low loss optical waveguides at 10.6 microns, the thickness of the waveguiding layer must be approximately 10 microns.

A study was made of various semiconductor materials that would be suitable for use as infrared waveguide substrates. Initially GaP, GaAs, ZnTe, ZnS, ZnSe, CdS and CdTe were considered because each of these materials has very promising optical and electrical characteristics. However, only GaAs, GaP and CdTe are commercially available in the required single crystal wafer form. It was decided to limit the present investigation to GaAs and GaP because CdTe is considerably more expensive and the processing technology for CdTe (polishing, etching, cleaning, heat treatment, etc.) is much more difficult. The wafers that were selected for implantation were <100> oriented substrates since these samples can be easily cleaved to the desired rectangular shape for waveguiding experiments.

Protons (H^+) were chosen as the initial ion species to be used in these implantation experiments in order to minimize the contributions to the optical properties arising from physical processes other than free carrier compensation. These ions produce the least amount of damage to the crystal and are very unlikely to occupy substitutional sites in the lattice. Furthermore, protons have the greatest projected range by direct energetic penetration without relying on any secondary or defect diffusion. In fact, protons are also a useful species for investigating such diffusion effects.

Since one of the basic objectives of this work is to produce waveguides of sufficient thickness to support low loss propagation at 10.6 microns while using a minimum implantation energy, 300 keV was selected as the ion energy to be used. Practical considerations make low energy very desirable because many electronics fabrication facilities are equipped with ion accelerators of 300 keV or less, while relatively few have units delivering greater than 300 KeV acceleration.

With 300 keV protons, calculations indicate that optical waveguides, of approximately three microns thick, can be produced in both GaAs and GaP provided that these materials have carrier concentrations on the order of $10^{18}/cm^3$. While such implanted layers could support guided waves at 10.6 microns, lower losses would be obtained if the thickness of these layers were increased. Several experimental investigations(9) have noted that the waveguide thickness is often increased beyond that produced by direct energetic ion penetration if the substrate is heated during the implantation process. This heating is expected to produce a diffusion of implantation generated defects, resulting in carrier compensation to a thickness as much as an order of magnitude greater than the penetration depth of the ions (protons) themselves. Because the defect diffusion process is not yet well characterized, the approach taken in this work is to use a range of implant temperatures spread both above and below room temperature by about 200 to 300°C to determine the optimum temperature empirically. Ion dose should be at least $5X10^{13}/cm^2$ to produce adequate carrier compensation in the waveguide but, again, some samples should be implanted with doses as high as $5X10^{15}/ cm^2$ to determine the optimum dose experimentally. Polished wafers of n-type GaAs have been implanted with protons to the required fluence levels and at the temperature ranges specified by this approach. The implantation of the wafers was performed at the Electronics Technology Division of the Naval Research Laboratory.

The next step in this investigation is to measure the optical index and thickness of the implanted layers. These parameters can be determined by the prism coupling method described in Section II. However, since the implanted layers are being designed to function at CO_2 laser wavelengths, an infrared detector is required to monitor waveguiding and to measure of the coupling angle. The experimental set up is illustrated by the insert in Figure 4. This infrared facility is presently being assembled and tested. Simultaneously, the optical properties of the implanted layers are being investigated using capacitance-voltage (C-V) measurements and ultraviolet/infrared reflectively techniques (10).

485

IV. CONCLUSIONS

Theoretical calculations and prior experimental work indicate the low loss infrared optical waveguides can be produced by 300 keV proton implantation of GaAs and GaP. Samples of these materials have been prepared and the resulting optical properties of the implanted layers, as determined from C-V and reflectivity measurements, are suitable for IR waveguiding. Once this is demonstrated and the relevant material and implantation parameters have been established, this method can be used for the fabrication of more complex guided wave structures such as channeled waveguides, directional couplers and modulators. These components can then be integrated to form infrared optical circuits for sensing and signal processing roles. Furthermore, it appears quite certain that such integrated optical circuits, with their greater bandwidth and faster operation, will play an increasingly larger role in helping the Army meet its future fire control requirements.

V. REFERENCES

1. "Army Fire Control Technology Base Plan (U), (6.1, 6.2., 6.3a), " Vol. I, U.S. Army DARCOM, (Conf.), 1978.

2. D. B. Anderson, "Integrated Optics RF Spectral Analyzer for Electronic Warfare", IEEE Spectrum, Vol. 15, No. 12, p 22 (1978).

3. N. J. Berg, J. N. Lee, M. W. Casseday and B. J. Udelson, Appl. Opt., Vol. 18, No. 16, p 2767 (1979).

4. C. Davis and R. Einzig, "Fiber Optic Sensor System (FOSS) Technology Assessment (U)", Dynamic Systems, Inc., Report No. 79-385-10-C, (Conf.), 1979.

5. D. L. Spears, "Integrated Optical Circuits Semiannual Technology Summary", Lincoln Laboratory, M.I.T., Report No. ESD-TR-75-103, 1979.

6. See, for example, D. Marcuse, Theory of Dielectric Optical Waveguides, Academic Press, New York, 1974.

7. J. E. Goell, "Thin-Film Waveguide Fabrication and Testing Considerations", in Introduction to Integrated Optics, M. K. Barnoski, Ed., Plenum Press, New York, 1974.

486

8. E. Garmire, "Semiconductor Components For Monolithic Applications", in Integrated Optics, T. Tamir, Ed., Springer-Verlag, New York, 1975.

9. R. G. Hunsperger, O. J. Marsh, and C. A. Mead, Appl. Phys. Letters, Vol. 13, p 295 (1968); R. G. Hunsperger and O. J. Marsh, Metal. Trans. Vol. 1, p 603 (1970).

10. J. M. Zavada, H. A. Jenkinson, T. J. Gavanis, R. G. Hunsperger, M. A. Mentzer, D. C. Larson, and J. Comas, Proc. of SPIE, 24th Intl. Symp. 1980.

487 – 488X

DAT

FILM